Taylor, Hugh Stott

The A B C's of science in oil recovery

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THE A B C'S OF SCIENCE IN OIL RECOVERY.

THE
A B C'S
OF SCIENCE IN
OIL RECOVERY,

—BY—

HUGH S. TAYLOR,

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PRINCETON UNIVERSITY;

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NATIONAL RESEARCH COUNCIL.

NEW YORK:
AMERICAN PETROLEUM INSTITUTE,
1927.

FOREWORD.

To give information and to bring about discussion, the article prepared by a leading physicist, and printed by the American Petroleum Institute is released for publication immediately.

A reasonable number of copies may be obtained free from the American Petroleum Institute, 250 Park Avenue, New York.

This is the first of a series of papers which will be prepared from time to time, and published by the American Petroleum Institute for the general information of the industry and the public. The articles will deal with the theory and practice of oil production, with especial reference to the conservation of gas, and to the consequent better control of production, and the increased recovery of oil.

The oil industry is about to enter a new era in which both the producer and the consumer, and the nation at large, the national defense and security, and the general welfare, will all obtain benefit.

THE AMERICAN PETROLEUM INSTITUTE,
250 Park Avenue, New York.
By R. L. WELCH, *General Secretary.*

May, 1927.

THE A B C's OF SCIENCE

—IN—

OIL RECOVERY.

EVERYTHING may exist in one or other or all of three different states, the solid, the liquid and the gaseous state. Thus, we have ice, water and water vapor (steam) as the solid, the liquid and the gas which we can obtain from water. We can change one form into another either by heating or cooling or by applying pressure or removing pressure. If we cool water we finally get solid water or ice. If we heat water we finally get water vapor or steam. Cooling steam yields water. In a similar manner, by applying high pressures to water, we can eventually solidify it to ice provided the water is not too hot. If we compress steam it will yield water. The hotter the steam the greater the pressure we must use to get liquid water from it. If we get water under such high pressure conditions, the steam is reproduced if we release the pressure. This is what happens when a steam boiler bursts. The water, upon the sudden release of the pressure, is rapidly changed into steam.

There is another way in which solids and gases may be given the form of liquid. This is familiar to everyone who has put a lump of sugar into coffee. The solid loses its shape and structure and becomes evenly distributed throughout the coffee, imparting to all the liquid the sweetness that it possessed as a solid. We say the sugar has dissolved in the coffee. We have a solution of sugar. Though not so familiar to everyone as is the case of sugar, it is also true that gases dissolve in liquids and give rise to solutions. One may observe

this often on drawing a glass of water suddenly from the cold water faucet. The clear water drawn from the spigot suddenly becomes cloudy and, looking closely, one observes innumerable tiny gas bubbles throughout the liquid. These gradually rise through the water and pass out into the air leaving clear water behind. The gas bubbles are composed of air dissolved in the water in the water mains which are under the pressure of the city water reservoirs. The gas is given up in part on release of the pressure. Not all the gas is thus given up. If we put the water in a vacuum more dissolved air will be given up. We thus see that the pressure is an important factor in determining how much of a gas is dissolved in a liquid.

We may learn more of this by another example, the familiar bottle of soda-water. Soda-water is nothing more than water which has been highly charged with carbonic acid gas under pressure. Hence its other name, carbonated water. The soda-water bottle when closed contains water in which the gas is dissolved at high pressure. If the cap be removed, the pressure is released and the dissolved gas begins to be liberated from the water. The rate at which the gas is liberated depends upon a number of things and the events which occur depend largely upon the rate at which the gas leaves the water. If we open the cap carefully we can slowly release the gas pressure and the liquid will remain in the bottle. It is still heavily charged with dissolved gas as can be shown on pouring rapidly into a glass. The motion of the water helps to release the gas and a sparkling glass of carbonated water results. If we shake the bottle of soda-water before opening and suddenly remove the cap, the release of gas occurs rapidly and is oftentimes so rapid as to carry along with it much of the water in the bottle. Such uncontrolled release of gas results in loss of material.

The pressure of the gas dissolved in the water may be put to use as the motive power for the removal of the water from the container. One way to accomplish this is to be seen in the soda-water syphon. In this case the carbonated water is drawn from a tube which reaches to the bottom of the bottle. As the syphon is opened the gas pressure in the space above

the liquid forces the water up the syphon tube and out into the receiving vessel. The water thus forced out still contains a lot of dissolved gas. The amount is determined by the pressure in the gas space above the liquid. The greater this pressure the more gas is dissoved in the water and vice versa. In a nearly empty syphon, since the gas volume above the liquid is now much larger than in a full syphon, the gas pressure is correspondingly less. The last water drawn from the syphon is consequently very much less carbonated—it is "flatter" and less sparkling—than that which comes from a fresh syphon.

All these familiar facts and observations are pertinent to the problem of oil under pressure underground and the methods to be adopted in bringing the oil to the earth's surface. Oil underground is a liquid which contains both dissolved solids and dissolved gas. Vaseline and paraffin wax are among the solids in solution in the oil, equivalent to the sugar dissolved in coffee. Natural gas is also in solution in oil just as carbonic acid gas is dissolved in soda-water. The amounts of solids and of gases dissolved in oil vary extremely widely in different oil fields giving vastly different types of oil. The general principles involved in these liquid solutions are, however, the same. They differ only in the degree with which they may be applied. It is the uncontrolled release of natural gas from oil underground that results in the production of "gushers," the parallel of which is the soda-water bottle suddenly opened. The syphon of soda-water is an example of a means whereby oil may be recovered from its reservoir under control utilizing as motive power the pressure of natural gas released from solution in the oil.

Oil underground is not, however, a simple pool of liquid containing dissolved solids and natural gas. The oil is found in sand or sandstone beds under layers of rock which make a gas-tight dome or cover for the oil reserve. To use the analogy of the soda-water bottle once more, the parallel would require that the bottle should be loaded with sand and having carbonated water in the spaces between the sand particles. On releasing the gas pressure it is apparent that the volume of liquid to be obtained would be considerably less than that

from a bottle of the same size without any sand. Several reasons account for this. In the first place, part of the volume is taken up by the sand. In the second place, part of the liquid remains behind, wetting the grains of sand. In the third place, with sufficiently fine sand, the liquid will be held to some extent in thin films between the sand particles. Let us examine the effect of these several factors on the possible yield from a bed of sand containing a given liquid.

First of all we may discuss the volume occupied by the sand. Let us think first of the sand as made up of perfectly round beads all of the same size. If these beads were all carefully arranged in an orderly manner so that each bead just touched six (and only six) other beads arranged regularly around it, it can be shown that the empty spaces between the beads in a bottle full of beads is about one-half (accurately 47.6 per cent) of the volume of the bottle. Our oil reservoir would only contain half its apparent volume of oil. This result does not depend upon the size of the beads. Large or small beads give the same result, provided they are all the same size and all have the arrangement indicated.

The arrangement is very important, however. That just discussed is known as the least compact arrangement. It gives the greatest volume of voids to hold our oil. If we shake down the beads into the most compact arrangement we shall then find that three-quarters of the bottle is occupied by beads, irrespective of their size, provided they are the same size. This leaves only one-quarter of the bottle to hold oil. Our oil reservoir is only one-quarter of its apparent size.

Conditions in nature are not so simple as this. The sand grains are not all one size but of very many sizes. This may result in an even smaller volume of space between the sand to be occupied by oil. For, we can imagine the case last considered, in which one-quarter of the whole volume was voids, to be mixed with smaller grains of sand that would sift into the spaces between the beads, still further reducing the capacity of the reservoir for oil. In this way we can see that it is not surprising that quite small fractions of an oil reservoir are really occupied by oil. Actually, measurement has shown in some cases that less than one-tenth of the whole reservoir

is occupied by oil. At the other extreme, as much as two-fifths of the sandy mass can be oil. Most actual oil fields show oil contents between these two extremes.

The size of the sand particles also influences the amount of oil which is left in a reservoir as a film of oil wetting the sand particles. When we empty a bottle of soda-water we always leave a thin film of water wetting the sides of the bottle. Actually this is a negligible portion of the total volume of water that the bottle can contain. If we fill the bottle with beads, we increase enormously the surface of glass which remains wet with water and so increase this loss of "wetting" water. The smaller the beads the more enormous does this surface become. If we halve the size of the beads we increase the surface four times. If we have beads one-quarter the size, the surface to be wet increases sixteen-fold. It can thus be seen that the finer the grains of sand in our oil reservoir the greater the surface of sand which will be wetted by oil. When this fact is coupled with our previous observation that varied sizes of sand grains may lead to an oil volume only one-tenth of the apparent volume it is obvious how important this size of sand grains becomes.

That, however, does not complete the picture with respect to size of sand on the yield of our reservoir. We have already found that with beads of equal sizes the amount of voids is the same whether the beads are large or small. But larger beads have much bigger pore areas than smaller beads. If we look again at our regular arrangement of beads in a bottle and concentrate our attention this time, not on the volume of the pore spaces but on the size of the holes between beads, we shall find that the size grows smaller much more rapidly than the size of the bead. Indeed, it can be shown that if we decrease the diameter of the beads by one-half we cut down the cross-sectional area between beads to one-quarter. If we reduce the diameter of the beads to one-quarter we cut down the cross-section to one-sixteenth. When we come down to actual sizes of sand these holes through the sand become extremely tiny. It has been calculated that, with an average sand (48 mesh), there are, in one cubic foot, as many as 1,500,000 pores in which oil may be stored, there are 4300

square feet of sand surface in direct contact with the oil, and the average size of the pore is such that 700 of them placed side by side would measure only one inch across. The problem of oil recovery, therefore, is a problem of drainage of oil from sands of such type and we have now to inquire what factors are of importance in determining the amount and also the time of drainage of oil from such sand beds.

Let us first focus our attention on the relation between the size of the pores through which the oil must flow and the time required for a given volume to flow. We may simplify our problem by considering, first of all, the flow of a liquid through a single pipe, which, for the purposes in view, may constitute one of the many pores in the sand. In a given time, the volume of liquid flowing through a tube diminishes very rapidly with decrease in the bore of the tube. Thus, if we decrease the bore of the tube to one-tenth, the volume flowing through diminishes to one ten-thousandth of that flowing through the larger tube. Thus, if we have two sands, each containing the same amount of oil, but differing in particle size so that the pores of one are only one-tenth the cross-sectional area of the other, then the times required for the same volume of the same oil to flow through each sand would be in the ratio of ten thousand to one. Since actual measurements of average pore diameters in different oil sands show variations as high as fifty to one it is not unexpected that different oil reservoirs show very varying rates of drainage. What is more important, however, is the varying rate of drainage with varying pore area in one and the same sand. It is apparent that when drainage of a reservoir first starts, the majority of the oil received will come from the largest pores. As these gradually exhaust, the rate of yield will slow up at a very rapid rate. Thus, if we assume, in a given sand, pore areas in the ratio of 100 to 1, a very conservative estimate, the rate of yield of the same oil from the largest and smallest pores will be in the ratio of 100 million to one. It is obvious that, if the initial flow from the largest pores is a practicable rate of flow, long before all the oil has been given up by the sand the yield rate will have become negligibly small. Everything has been discussed in these paragraphs from the standpoint of spherical particles of sand. This has permitted quantitative statements. In practice, however, the particles are not spherical and are of unequal size. In general this will result in even smaller pores than those discussed and, hence, an exaggeration of the effects noted.

Let us turn now to the pressure factor. The amount of oil flowing through a given pipe increases directly as the pressure applied to force it through the pipe. Applying this to the problem of sand drainage it is apparent that the greater the head of pressure between the reservoir dome and the oil outlet the greater will be the rate at which the oil is yielded by the sand. This points to the desirability, so far as this factor is concerned, of maintaining in the oil dome as much of the natural gas pressure as circumstances allow.

Everyone knows that there are great differences in the ease with which liquids flow. Molasses flows much more slowly from a vessel than does water under the same conditions. These differences in rate of flow are of importance in the problem of oil drainage where there are as great differences among oils in this property of fluidity as there is between molasses and water. Gasoline is the most fluid fraction of the oil. Lubricating oil is one of the less fluid or more viscous fractions. By adding a more fluid to a less fluid constituent we increase the fluidity of the heavier part. Every automobile owner knows this fact in the problem of crank case dilution. The lubricating oil becomes more fluid by admixture of gasoline with the lubricating oil in the cylinders of the engine.

Now, just as gasoline increases the ease of flow of a heavier oil when mixed with it, so, also, the introduction of natural gas into a heavy oil increases its fluidity. The more gasoline we introduce into a heavy oil the more we thin the oil. Similarly, the more natural gas we introduce into a heavy oil the more we thin it. We can increase the amount of natural gas dissolved in oil in exactly the same way that the soda-water manufacturer increases the carbonic acid gas in his carbonated water, namely, by pumping the gas into the liquid under pressure. The more pressure we apply, the

more natural gas dissolves in the oil. If we double the pressure, we roughly double the amount of natural gas dissolved. Now the effect of the natural gas as a thinner for the oil is even more pronounced, weight for weight, than the effect of gasoline. Also, its effect on the oil is roughly proportional to the amount introduced. We shall increase the fluidity twice as much by dissolving twice the amount of gas, or, what is the same thing, by doubling the gas pressure.

Crude oil underground is generally heavily charged with natural gas, frequently at pressures as great as 2000 lbs. per square inch. This means that the oil contains large quantities of dissolved natural gas, and this gas will, as we have seen, very much increase the fluidity of the oil and aid its flow through the pores of the sand into the collecting pools. This gas will remain in the crude oil so long as the pressure is maintained on the oil, just as our soda-water remains charged with gas so long as it is in a closed vessel. But, if we release the pressure on our soda-water, the gas is given off and the water becomes "flat"; it has lost most of the dissolved gas. In exactly the same way if we release the gas pressure on our oil wells the gas is given off as natural gas and the crude oil remains behind free from gas. But, the consequence of most importance in such release of natural gas is that the crude oil loses the fluidity which the presence of the natural gas gave to it. It flows then very much less readily and collects more slowly in the drainage pools.

Let us take some examples from actual experiments which will show how great this effect can be. It has been found that a crude oil which contains natural gas dissolved in it at 500 pounds pressure per square inch flows just twice as rapidly as it would under the same conditions if it contained no dissolved gas. This means that, in the same period of time, twice as much oil would drain from a given bed if the oil were kept saturated at the given pressure as would be obtained if the gas were first allowed to escape from the liquid and this latter was then drained from the oil reserve. Since pressures as high as 1000 lbs. per square inch or greater are not uncommon in oil producing areas it follows that drainage may be secured, by pressure maintenance, at

as much as four times the possible rate of flow of oil from which the natural gas pressure is released.

We have seen previously that the size of pores determines in part the rate of flow of oil from the area and that the pores may be so fine as to cause impracticably low rates of flow. By maintaining gas pressure and thus increasing flow rates by upwards of two to four times it is apparent that one result will be that the range of pore sizes from which practicable speeds of flow may be secured will be correspondingly increased. The effect, therefore, of maintenance of gas pressure on the fluidity of the oil is twofold; it increases the rate of yield of oil and also the total amount of yield attainable in practice. Any uncontrolled release of gas pressure will have its effect upon ultimate oil recovery, but in some cases an apparently large amount of gas must necessarily be produced to win the oil even though by such gas production pressure is reduced.

We noted earlier that, as the syphon of soda-water empties, the pressure of gas above the liquid decreases and the amount of gas dissolved in the soda-water becomes less. The last water from the syphon is less sparkling than the first. The same is true of our oil reserve. Even if we recover the oil without release of pressure the voids left by the oil drainage become filled with gas released from the remaining oil. This latter becomes, therefore, less saturated with gas and consequently less fluid. Its recovery becomes correspondingly slower and less complete. We could keep our soda-water sparkling to the last drop if we could re-introduce into the syphon gas sufficient to make up the original pressure. We can keep our oil fluid under drainage if we re-introduce natural gas to the oil bed to maintain the original gas pressure. From the point of view of oil flow and oil conservation, therefore, it is not only desirable to prevent indiscriminate loss of natural gas pressure but even to reinforce this pressure against the ordinary loss of pressure due to drainage by return of gas under pressure to the area.

Gases do not all dissolve in liquids to the same extent. Carbonic acid gas is much more soluble in water than is air. Under the same conditions five times as much carbon dioxide

dissolves. It is the quantity dissolved, not the working pressure, which is of importance in the lowering of the fluidity of oil by dissolved gases; just as with water there are great differences in the solubility of natural gas and other gases in oil. For example, a natural gas composed principally of methane is less than four-fifths as soluble as a natural gas containing roughly half and half methane and ethane. This means that it is roughly only four-fifths as useful, under comparable conditions, in increasing the fluidity of the oil. Actual test showed that it was only three-fifths as good. It is evident, therefore, that attention should be paid not only to maintaining gas pressure in the oil area but also to the type of gas used for maintenance of the pressure. From the standpoint of fluidity, a pressure of "rich" natural gas would be very much better than a pressure of "lean" natural gas, although economic factors might prevent such a procedure.

It is not essential that the gases used in maintaining pressure be natural gas. Any gas that is very soluble in oil will serve equally well. It is well known that carbonic acid gas, our constituent of soda-water, is also freely soluble in many liquids of the type of oil. Indeed, it has been shown that, actually, this gas is more soluble in crude oil than the better of the two natural gases discussed above. Carbonic acid gas should, therefore, and does have a greater influence than these natural gases on the fluidity of the crude oil. Its use, obviously, would depend on its availability at the well. This involves chemical problems which can, however, be satisfactorily solved.

The possibility of using other gases than natural gas also brings up the question of the possible use of air and also of hydrogen. The former is available and the latter can be produced from raw materials at hand. Neither of these gases, however, is very soluble in crude oil and their efficiencies could not be expected to be more than a small fraction of those attainable with natural gas or with carbon dioxide. In the case of air, also, since chemical reaction may occur between the oil and the oxygen the results obtained would depend in part on whether these reactions gave more viscous or less viscous products.

There is one other factor which influences the fluidity of an oil, and that is the temperature. The hotter the oil the more readily it flows. Since deep wells are hotter than shallow wells we may expect greater proportionate recoveries of oil from deep wells. There does not seem, however, to be any simple practicable method whereby the temperature of a given well can be increased to give the advantage of greater rate of flow with hotter conditions. Also, the hotter the oil, the less the gas which it will dissolve under a given pressure. Hence, the hotter the oil the less the effect to be obtained from maintaining the gas pressure, though the differences caused by the temperature are of secondary magnitude.

There is one other factor that helps to prevent the oil operator from recovering all the oil from a given area. The scientist calls that factor the surface tension. Anyone can show the operation of surface tension by allowing the tip of a handkerchief to touch the surface of a bowl of water. Close observation will show that the water is "sucked up" by the handkerchief well above the level of the water in the bowl. The water rises to higher levels in the fine pores of the handkerchief than it occupies in the bowl of water. The scientist measures surface tension in just this way. He measures the height to which the liquid will rise above the level of a liquid, when a fine tube of known bore is introduced into the liquid. The greater the surface tension the higher it will rise. Anything which lowers the surface tension will decrease the height to which the liquid will rise. A little soap in water lowers its surface tension and the rise can easily be reduced to half its normal value.

The bed of oil sand is, as we have seen, a fine network of tiny pores acting in the same manner as the tube of fine bore or the handkerchief which we have just discussed. Drainage from such a sand bed would be incomplete even if all the factors already discussed in detail were not operating at all. Anyone can convince himself that this is so by allowing a brick to dip just below the surface of water. Water will be drawn up gradually into all the pores of the brick until it is all moist. In this way too we can actually measure the possible recovery of liquid. All that it is necessary to do is to

weigh first of all the dry brick, secondly the brick after it has touched the water surface and taken up all it is able, and finally the weight of the brick after total immersion in water. The difference between the first and third will be the weight of water the brick can hold. The difference between the first and second is the weight which would be retained by surface tension. The same holds true for the oil in the sand. To the extent that sand is capable of drawing up oil into its pores by that amount is drainage of such an area incomplete by reason of surface tension.

Just as we can lower the surface tension of water by the addition of soap so we can modify the surface tension of oil. Anything which decreases the surface tension of the oil facilitates oil recovery. All that has been written as to the effect of pressure on the fluidity of oil is applicable alike to the lowering of the surface tension. The percentage effect in this case is not so great as in the case of fluidity but it is still sufficient to influence the drainage of oil to a marked degree. Thus, whereas a pressure of 500 lbs. per square inch causes the oil to flow twice as fast, the change in surface tension was about 25 per cent. There is room for much work on the surface tensions of oils and their modification by the addition of substances which would lower their surface tensions and thus promote their expulsion from the sand areas.

There are problems of operation in the use of pressure in oil fields which are not touched upon in this survey. They relate to by-passing of less depleted areas and reversal of flow between non-depleted and depleted areas. These problems are essentially local and call for study each individually. What have been here presented are the generalized scientific principles of the problem and they are offered to the industry in the hope that they may be stimulative of thought and productive of application.

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